New $\beta_s$ measurement at CDF

- Introduction
  - Context
  - SM description

- The measurement
  - Fit strategy
  - Signals
  - Flavor tagging

- Results
The Context

- Great SM success in $B_d/B_u$ sector
  - Thanks B-factories!
  - ...but no evidence for new physics there

- Bs sector can still provide surprises
  - Natural physics for Tevatron experiments
  - In 2006 $\Delta m_s$ measurement from Bs mixing
    - Right on the SM expectations!
  - Next step is measurement of CP violating phases eg. $\beta_s$
    - ...some excitement there so far

$A/\sigma_A = 6.05$
Previous CDF+D0 combined results intriguing
Related measurements

- Semileptonic asymmetry
  - Related to $\Delta \Gamma$, $\Delta m$ and $\beta$s
  - SM expectation $\sim 10^{-5}$

- Old results from CDF and D0:

![CDF and D0 results graph]

- Intriguing new D0 result
\( \beta_s \) in SM

- \( \beta_s \) is the phase of \(-V_{ts}\)
  - \( \neq 0 \) in O(\(\lambda^4\)) CKM expansion

\[
V_{\text{CKM}} = 1 - \frac{\lambda^2}{2} - \frac{\lambda^4}{8} - \lambda - A^2 \lambda^5 (\rho + i\eta - \frac{1}{2}) + O(\lambda^6)
\]

- Quite well constrained assuming SM and very small

\[
\beta_s^{\text{SM}} = \text{arg} \left[ -V_{ts} V_{tb}^*/(V_{cs} V_{cb}^*) \right] = 0.01812 \pm 0.0008
\]

CKM fitter. Sept. 2009

All real

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Basic Theory

2 state effective theory:

- Describes mixing and CP violation
- \( M, \Gamma \) hermitian
  - CPT invariance: \( M_{11} = M_{22}, \Gamma_{11} = \Gamma_{22} \)
- After diagonalization:
  - Eigenvalues:
    \[
    \lambda_{\pm} = (m \pm \Delta m) - \frac{i}{2}(\gamma \pm \Delta \gamma)
    \]
    \[
    = m - \frac{i}{2} \gamma \pm \sqrt{(m_{12} - \frac{i}{2} \gamma_{12})(m_{12}^* - \frac{i}{2} \gamma_{12}^*)}
    \]
  - Eigenstates:
    \[
    |B_s^H\rangle = p |B_s^0\rangle - q |\bar{B}_s^0\rangle \quad |B_s^L\rangle = p |B_s^0\rangle + q |\bar{B}_s^0\rangle
    \]
Origin of off-diagonal terms

- $m_{12}$ from box diagram
  - Top quark dominant
  - $M_{12} \propto V_{ts}^2 \propto e^{-2i\beta_s}$

- New physics possible in loops!
  \[
  M_{12} = |M_{12}| \cos \theta_N \phi_P
  \]

- $\Gamma_{12}$ from common final states
  - For $B_s$ dominated by $D_s^+ D_s^-$
    - $\Delta \Gamma/\Gamma \sim 0.10$
    - $\Gamma_{12}$ mostly real: $\phi_s \sim -2\beta_s$
  - Tree level dominated
    - Hard to see new physics here

\[
\Gamma_{12} = \sum_f <B|f> \rho_f <f|\bar{B}>
\]

\[
\Delta \Gamma = 2 \text{Re}\{\Gamma_{12}/m_{12}\} m_{12} |m_{12}| = 2 |\Gamma_{12}| \cos \phi
\]
**Measured quantities**

- **Mixing frequency (theory limited):**
  \[ \Delta M = 2 |M_{12}| \]

- **Width difference (statistics limited):**
  \[ \Delta \Gamma = 2|\Gamma_{12}| \cos \phi \]

- **Semileptonic asymmetry (stat.+syst. limited):**
  \[ A_{SL} = -\frac{|\Gamma_{12}|}{\Gamma_{T2}} \sin \bar{\Delta} = \frac{\phi}{M} \tan \bar{\Delta} \]

- **Bs – Bs bar interference in decay to common final state such as J/ψ φ (statistics limited):**
  \[ -\text{Im}(p/q) \sim \sin(2\beta_s) \sim -\sin \phi \]

This measurement
Analysis strategy

Study time evolution of $B_s \rightarrow J/\psi \phi$ decay

- No SM weak phases in $A_f$ such that $A_{\perp} = 1$
  - Sign depends on CP of final state
- ... but $J/\psi \phi$ is vector-vector $\rightarrow$ mixture of CP-even and CP-odd
  - Need to perform full angular analysis to separate the components
    - L=0 and L=2 are CP-even, L=1 is CP-odd
    - Prefer to use "transversity basis": $A_0$, $A_{\|}$: CP-even, $A_{\perp}$: CP-odd
- Need to introduce more hadronic decay amplitudes and their phases:
  - $A_0$, $A_{\|}$, $A_{\perp}$ such that $|A_0|^2 + |A_{\|}|^2 + |A_{\perp}|^2 = 1$, $\delta_{\|}$, $\delta_{\perp}$ (phases relative to $A_0$)

\[< f J\mathcal{B}(t) > = \epsilon_i e^{imt} \epsilon_i e^{i2A_f \cos(\phi mt)} \epsilon^{+\phi \sin(\phi mt)} \]
Full Bs decay rate formula

\[
\frac{d^4 P(t, \vec{\rho})}{dt d\vec{\rho}} \sim |A_0|^2 T_+ f_1(\vec{\rho}) + |A_\parallel|^2 T_+ f_2(\vec{\rho}) + |A_\perp|^2 T_- f_3(\vec{\rho}) + A_\parallel A_\perp U_+ f_4(\vec{\rho}) + |A_0| |A_\parallel| \cos(\delta_\parallel) T_+ f_5(\vec{\rho}) + |A_0| |A_\perp| \nu_+ f_6(\vec{\rho}),
\]

- Identification of \( B \) flavor at production (flavor tagging) \( \rightarrow \) better sensitivity to \( \beta_s \)

\[
T_\pm = e^{-\Gamma t} \times \left[ \cosh(\Delta \Gamma t/2) \mp \cos(2\beta_s) \sinh(\Delta \Gamma t/2) \mp \eta \sin(2\beta_s) \sin(\Delta m_s t) \right],
\]

\[
U_\pm = \pm e^{-\Gamma t} \times \left[ \sin(\delta_\perp - \delta_\parallel) \cos(\Delta m_s t) - \cos(\delta_\perp - \delta_\parallel) \cos(2\beta_s) \sin(\Delta m_s t) \pm \cos(\delta_\perp - \delta_\parallel) \sin(2\beta_s) \sinh(\Delta \Gamma t/2) \right]
\]

\[
\nu_\pm = \pm e^{-\Gamma t} \times \left[ \sin(\delta_\parallel) \cos(\Delta m_s t) - \cos(\delta_\parallel) \cos(2\beta_s) \sin(\Delta m_s t) \pm \cos(\delta_\parallel) \sin(2\beta_s) \sinh(\Delta \Gamma t/2) \right].
\]

- \( \delta_\parallel \equiv \text{Arg}(A_\parallel(0)A_0^*(0)) \)
- \( \delta_\perp \equiv \text{Arg}(A_\perp(0)A_0^*(0)) \)
Improvements over past

- Luminosity: 2.9 → 5.2 fb⁻¹
- Signal optimization with NN
- ~ 6500 Bs → J/ψφ, S/N ~ 1
- Improved flavor tagging completely recalibrated (see later)
- Inclusion of f₀ scalar component (Bs → J/ψf₀) (see later)

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Flavor tagging

- Opposite side (OST)
  - Jet / lepton charge
  - Combined with NN
  - Calibrate with 52,000 \( J/\psi K^+ \)
  - \( \varepsilon = 94.2 \pm 0.4\% \), \( D = 11.5 \pm 0.2\% \)
    \( \varepsilon D^2 = 1.2\% \)

- Same side Kaon (SSKT)
  - Sign of soft kaon near Bs
  - Dilution from simulation
  - Calibrate with \( \sim 13,000 \) Bs \( \rightarrow Ds(3)\pi \)
    - From mixing amplitude scan
    - \( \varepsilon D^2 = 3.2 \pm 1.4\% \)

\( \Delta m_s = 17.79 \)

Old CDF result

CDF Run 2 Preliminary, \( L = 5.2 \text{ fb}^{-1} \)

\.Errorf[Amplitude A]

\( \Delta m_s = 17.77 \pm 0.10 \text{ (stat)} \pm 0.07 \text{ (syst)} \text{ ps}^{-1} \)

Mixing Frequency in ps\(^{-1}\)
Results: Bs lifetime & $\Delta \Gamma$

- **Point measurement assuming SM**
  - Set $\beta_s = 0$
  - Most precise measurement of $B_s$ lifetime and $\Delta \Gamma$

\[
\tau_s = 1.53 \pm 0.025 \text{ (stat.)} \pm 0.012 \text{ (syst.)} \text{ ps}
\]
\[
\Delta \Gamma = 0.075 \pm 0.035 \text{ (stat.)} \pm 0.01 \text{ (syst.)} \text{ ps}^{-1}
\]

PDG 2009 averages:
\[
\tau_s = 1.472^{+0.024}_{-0.026} \text{ ps}
\]
\[
\Delta \Gamma = 0.062^{+0.034}_{-0.037} \text{ ps}^{-1}
\]

$CP$-even ($B_s^{\text{light}}$) and $CP$-odd ($B_s^{\text{heavy}}$) components have different lifetimes
\[
\rightarrow \Delta \Gamma \neq 0
\]
**Results: polarization amplitudes**

- **$\beta s = 0$ fit**
  - Most precise measurement

\[
|A_\parallel(0)|^2 = 0.231 \pm 0.014 \text{ (stat)} \pm 0.015 \text{ (syst.)}
\]
\[
|A_0(0)|^2 = 0.524 \pm 0.013 \text{ (stat)} \pm 0.015 \text{ (syst.)}
\]
\[
\phi_\perp = 2.95 \pm 0.64 \text{ (stat)} \pm 0.07 \text{ (syst.)}
\]
Full fit results

- Low statistics & dilutions
  - Some parameters very non-Gaussian, including $\beta_s$
- Contours corrected for
  - Non-gaussian effects
  - Systematics
- Note fit symmetry
  - $2\beta_s \rightarrow \pi - 2\beta_s$
  - $\delta_\parallel \rightarrow 2\pi - \delta_\parallel$
  - $\Delta \Gamma \rightarrow -\Delta \Gamma$
  - $\delta_\perp \rightarrow \pi - \delta_\perp$

$\beta_s$ projection

- $[0.02, 0.52] \cup [1.08, 1.55]$ at 68% C.L.
Effect of s-wave resonance


- Effect of Bs → J/ψ f_0
  - Fit prefers ~ 2%
  - Consistent with m(KK) fit
  - < 6.7% @ 95% CL

![Graph showing CDF Run II Preliminary results with 95% and 68% CL regions, indicating not adjusted for non-Gaussian errors.](image)
Conclusions & prospects

- Best measurement of Bs lifetime, $\Delta \Gamma$ and polarization amplitudes
- Tighter constraints on $\beta_s$
  - Improved agreement with SM ($\sim 1\sigma$)
- Future improvements
  - Statistics doubled ($10 \text{ fb}^{-1}$) by end of 2011 Tevatron run
  - More data $\sim 25$-$30\%$ from track based triggers
  - Additional decay modes:
    - $\psi(2S)\phi$
    - $J/\psi f_0, f_0 \rightarrow \pi \pi$ (CP-eigenstate)
Getting hot

CDF+DØ

LHCb

Tevatron 2011: discover or exclude NP in wide range of phases.

LHCb competitive (if everything turns out as expected)
Opposite Side Tagging Calibration and Performance

- OST combines in a NN opposite side lepton and jet charge information
- Initially calibrated using a sample of inclusive semileptonic $B$ decays
  - predicts tagging probability on event-by-event basis
- Re-calibrated using $\approx 52,000 \, B^{+/−} \rightarrow J/\Psi \, K^{+/−}$ decays

- OST efficiency = $94.2 \pm 0.4\%$, OST dilution = $11.5 \pm 0.2 \%$
- Total tagging power = $1.2\%$

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Same Side Tagging Calibration

- Event-by-event predicted dilution based on simulation
- Calibrated with 5.2 fb⁻¹ of data
- Simultaneously measuring the $B_s$ mixing frequency $\Delta m_s$ and the dilution scale factor $A$

$$P_{Sig}(ct|\sigma_{ct}, \xi = \xi_D \cdot \xi_P, D) = \frac{1}{N} \cdot \left[ \frac{1}{\tau} e^{-t/\tau} \cdot (1 + \xi AD \cdot \cos(\Delta m_s \tilde{t})) \right] \otimes G(ct|\sigma_{ct}) \cdot \epsilon(ct|\sigma_{ct})$$

- $D$ – event by event predicted dilution
- $\xi$ – tagging decision = +1, -1, 0 for $B_s$, $B_s$ and un-tagged events

- Fully reconstructed $B_s$ decays selected by displaced track trigger

<table>
<thead>
<tr>
<th>Decay Channel</th>
<th>$S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0 \to D_s^- \pi^+$, $D_s^- \to \phi\pi^-$</td>
<td>5613 ± 75</td>
</tr>
<tr>
<td>$B_s^0 \to D_s^- \pi^+$, $D_s^- \to K^* K^-$</td>
<td>2761 ± 53</td>
</tr>
<tr>
<td>$B_s^0 \to D_s^- \pi^+$, $D_s^- \to (3\pi)^-$</td>
<td>2652 ± 52</td>
</tr>
<tr>
<td>$B_s^0 \to D_s^- (3\pi)^+$, $D_s^- \to \phi\pi^-$</td>
<td>1852 ± 43</td>
</tr>
</tbody>
</table>

Sum 12877 ± 113
- $CP$ even and $CP$ odd final states have different angular distributions
  $\rightarrow$ use angles $r = (\theta, \phi, \psi)$ to statistically separate $CP$ even and $CP$ odd components

- Detector acceptance distorts the angular distributions
  $\rightarrow$ determine 3D angular efficiency function from simulation and account for this effect in the fit

CDF Simulation of Detector Angular Sculpting
As noted in arxiv:0812.2832v3, the final state in $B_s \rightarrow J/\Psi KK$ decays can be in an s-wave state with a ~6% contribution in a +/-10 MeV window around the $\Phi$ peak.

Systematic effects from neglecting such contribution were first investigated by Clarke et al in arxiv:0908.3627v1 where it is shown that:

- 10% un-accounted s-wave contamination in the $\Phi$ region leads to
  - 10% bias in the measured $2b_s$, towards the SM prediction
  - 15% increase in statistical errors

S-wave contribution can be either non-resonant or from the $f^0(980)$ resonance.

To account for potential s-wave contribution, enhance the likelihood function to account for the s-wave amplitude $A_s$ and interference between s-wave and p-wave.

Time dependence of the s-wave amplitude $A_s$ is $CP$-odd, same as $A_{\perp}$.

Mass and phase of s-wave component are assumed flat (good approximation in a narrow +/- 10 MeV around the $\Phi$ mass).
S-Wave Cross Check Using KK Mass Spectrum

- Cross check the result from angular fit by fitting the KK invariant mass spectrum

- From a fit to the $B_s$ mass distribution with wide KK mass range selection (0.980, 1.080 GeV), determine contributions of combinatorial background, mis-reconstructed $B^0$, and $B_s$ events

- Good fit of the KK mass spectrum with 2% $f^0$ contributions

Barely visible S-wave component
Non-Gaussian Regime

- Pseudo-experiments show that we are still not in perfect Gaussian regime
  → quote confidence regions instead of point estimates

- In ideal case (high statistics, Gaussian likelihood), to get the 2D 68% (95%) C.L. regions, take a slice through profiled likelihood at 2.3 (6.0) units up from minimum

- In this analysis integrated likelihood ratio distribution (black histogram) deviates from the ideal $c^2$ distribution (green continuous curve)

- Using pseudo-experiments establish a “map” between Confidence Level and 2Dlog(L)

- All nuisance parameters are randomly varied within +/- 5σ from their best fit values and maps of CL vs 2Dlog(L) re-derived

- To establish final confidence regions use most conservative case

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Systematic Uncertainties

| Systematic                                      | $\Delta \Gamma$ | $c\tau_s$ | $|A_{||}(0)|^2$ | $|A_0(0)|^2$ | $\phi_\perp$ |
|------------------------------------------------|-----------------|-----------|----------------|--------------|-------------|
| **Signal efficiency:**                          |                 |           |                |              |             |
| Parameterisation                                | 0.0024          | 0.96      | 0.0076         | 0.008        | 0.016       |
| MC reweighting                                  | 0.0008          | 0.94      | 0.0129         | 0.0129       | 0.022       |
| **Signal mass model**                           |                 |           |                |              |             |
|                                                   | 0.0013          | 0.26      | 0.0009         | 0.0011       | 0.009       |
| **Background mass model**                       |                 |           |                |              |             |
|                                                   | 0.0009          | 1.4       | 0.0004         | 0.0005       | 0.004       |
| **Resolution model**                            |                 |           |                |              |             |
|                                                   | 0.0004          | 0.69      | 0.0002         | 0.0003       | 0.022       |
| **Background lifetime model**                   |                 |           |                |              |             |
|                                                   | 0.0036          | 2.0       | 0.0007         | 0.0011       | 0.058       |
| **Background angular distribution:**             |                 |           |                |              |             |
| Parameterisation                                | 0.0002          | 0.02      | 0.0001         | 0.0001       | 0.001       |
| $\sigma(c\tau)$ correlation                    | 0.0002          | 0.14      | 0.0007         | 0.0007       | 0.006       |
| Non-factorisation                               | 0.0001          | 0.06      | 0.0004         | 0.0004       | 0.003       |
| $B^0 \rightarrow J_\psi K^*$ crossfeed          | 0.0014          | 0.24      | 0.0007         | 0.0010       | 0.006       |
| SVX alignment                                   | 0.0006          | 2.0       | 0.0001         | 0.0002       | 0.002       |
| Mass error                                      | 0.0001          | 0.58      | 0.0004         | 0.0004       | 0.002       |
| $c\tau$ error                                   | 0.0012          | 0.17      | 0.0005         | 0.0007       | 0.013       |
| Pull bias                                       | 0.0028          |           | 0.0013         | 0.0021       |             |

**Totals**                                        | 0.01            | 3.6       | 0.015          | 0.015        | 0.07        |